

# Target and Double Spin Asymmetries of Deeply Virtual $\pi^0$ Production with a Longitudinally Polarized Proton Target and CLAS

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The target and double spin asymmetries of the exclusive pseudoscalar channel  $\vec{e}\vec{p} \rightarrow ep\pi^0$  were measured for the first time in the deep-inelastic regime using a longitudinally polarized 5.9 GeV electron beam and a longitudinally polarized proton target at Jefferson Lab with the CEBAF Large Acceptance Spectrometer (CLAS). The data were collected over a large kinematic phase space and divided into 110 four-dimensional bins of  $Q^2$ ,  $x_B$ ,  $-t$  and  $\phi$ . Large values of asymmetry moments clearly indicate a substantial contribution to the polarized structure functions from transverse virtual photon amplitudes. The interpretation of experimental data in terms of generalized parton distributions (GPDs) provides the first insight on the chiral-odd GPDs  $\tilde{H}_T$  and  $E_T$ , and complement previous measurements of unpolarized structure functions sensitive to the GPDs  $H_T$  and  $\bar{E}_T$ . These data provide necessary constraints for chiral-odd GPD parametrizations and will strongly influence existing theoretical handbag models.

The introduction of generalized parton distributions (GPDs) [1–3] defines a new important and far-ranging theoretical framework that allows for the description of the angular momentum components of quarks and gluons in the proton in terms of density distributions in both longitudinal momentum fraction and transverse spatial degrees of freedom. They provide information on the orbital motion of partons, rendering a three dimensional view of hadron structure [4, 5]. Therefore, GPDs offer an unprecedented opportunity to investigate the nucleon internal structure and provide insight into the hadron at the quark-gluon level.

At leading twist there are eight GPDs [5] for each quark flavor  $q$ : four correspond to parton helicity conserving (chiral-even) processes, denoted as  $H^q$ ,  $E^q$ ,  $\tilde{H}^q$ ,  $\tilde{E}^q$ , and the remaining four,  $H_T^q$ ,  $E_T^q$ ,  $\tilde{H}_T^q$ ,  $\tilde{E}_T^q$ , correspond to parton helicity-flip (chiral-odd) processes. The conventional  $\bar{E}_T = 2\tilde{H}_T + E_T$  will be used as well hereafter. These GPDs can be accessed from the hard exclusive processes such as deeply virtual exclusive photon and meson electroproduction. Deeply virtual pseudoscalar meson electroproduction is sensitive to the chiral-odd GPDs which are less-known than their chiral-even counterparts, because they are not accessible in deeply virtual Compton scattering and, generally, their contributions are suppressed [6, 7]. However, their knowledge is essential since they open a new avenue to access the quark transversity distribution,  $h_1$ , and encode unique information on the transverse spin structure of the proton and on the tensor charge [6].

Deeply virtual  $\pi^0$  electroproduction, as evidenced in the data from the CEBAF Large Acceptance Spectrometer (CLAS) [8–10], was identified as especially sensitive to the helicity-flip subprocesses. The inclusion of twist-3 components calculated using the chiral-odd GPD parametrizations leads to sizable transverse virtual photon amplitudes and brings theoretical calculations into

agreement with the unpolarized cross section measurements. However, while the measurements of the unpolarized structure functions and beam spin asymmetries for deeply exclusive  $\pi^0$  production have been obtained by the CLAS [8–10] and Hall A Collaborations [11], there are no experimental data available on a longitudinally polarized target. This work presents the first extraction of target and double spin asymmetries for deeply virtual  $\pi^0$  production.

The interpretation of spin asymmetries is more complicated in comparison with unpolarized cross-sections. Firstly, the measured asymmetries are the ratios of polarized structure functions and the unpolarized cross section, so the knowledge of unpolarized structure functions is necessary to isolate the polarized contribution. Secondly, the polarized structure functions are calculated as products of chiral-even and chiral-odd GPDs, complicating the separation of the different contributions. Spin asymmetries, however, provide a unique opportunity to access chiral-even as well as chiral-odd GPDs simultaneously.

Spin asymmetries are defined as a ratio of the difference over the sum of cross sections for opposite helicity configurations and they can be expressed as:

$$A_{UL} = \frac{A_{UL}^{\sin\phi} \sin\phi + A_{UL}^{\sin 2\phi} \sin 2\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos 2\phi} \cos 2\phi}, \quad (1)$$

$$A_{LL} = \frac{A_{LL}^{\text{const}} + A_{LL}^{\cos\phi} \cos\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos 2\phi} \cos 2\phi}, \quad (2)$$

where the first index  $U$  ( $L$ ) stands for unpolarized (longitudinally polarized) beam, the second index  $U$  ( $L$ ) for the target polarization and  $\phi$  is azimuthal angle between the lepton and hadron scattering planes.  $A_{UU}^{\cos\phi}$  and  $A_{UU}^{\cos 2\phi}$  are connected to the unpolarized structure functions, common for the beam, target and double spin

asymmetries, and  $A_{UL}^{\sin\phi}$ ,  $A_{UL}^{\sin 2\phi}$ ,  $A_{LL}^{const}$ ,  $A_{LL}^{\cos\phi}$  are connected to the polarized structure functions. These polarization observables are sensitive to their own compositions of various contributing GPD convolutions  $\langle F \rangle$ , where  $\langle F \rangle$  is the convolution of hard scattering amplitudes and GPDs [7, 12] defined as

$$\langle F \rangle = \sum_{\lambda} \int_{-1}^1 dx \mathcal{H}(x, \xi, Q^2, t) F(x, \xi, t), \quad (3)$$

where  $F$  represents a “generic” GPD and  $\mathcal{H}$  is a partonic subprocess amplitude.

The measurements of unpolarized cross sections showed strong sensitivity of the  $\pi^0$  electroproduction to the  $H_T$  and  $\tilde{E}_T$  GPDs [9, 10]. Conversely, the target and double spin asymmetries from deeply virtual  $\pi^0$  electroproduction are expected to provide access to  $\tilde{H}_T$  and  $E_T$  terms within the GGL model [13]. As of today, these two GPDs are not constrained by any experimental data, and  $\pi^0$  target and double spin asymmetries presented in this paper provide a first experimental insight. In particular, the constant term in the double spin asymmetry is dominated by  $\langle H_T \rangle$  and  $\langle \tilde{H}_T \rangle$ , the  $A_{UL}^{\sin\phi}$  term is sensitive to the imaginary parts of chiral-odd and chiral-even GPD compositions  $\langle \tilde{E}_T \rangle^* \langle \tilde{H} \rangle$  and  $\langle H_T \rangle^* \langle \tilde{E} \rangle$ ,  $A_{LL}^{\cos\phi}$  is sensitive to the real part of the same compositions and  $A_{UL}^{\sin 2\phi}$  is determined by  $\langle \tilde{H}_T \rangle$  and  $\langle E_T \rangle$  [13].

We present the first measurements of longitudinally polarized target and double spin asymmetries for deeply virtual  $\pi^0$  electroproduction over a large phase space. The experiment was carried out in 2009 in Hall B at Jefferson Lab, using CLAS [14], a longitudinally polarized electron beam with average energy of 5.9 GeV and a longitudinally polarized solid ammonia target [15]. The target system, based on a 5 T superconducting magnet and a 1 K  $^4\text{He}$  refrigerating bath, was constructed to polarize protons in paramagnetically doped  $^{14}\text{NH}_3$  along the beam direction via the dynamic nuclear polarization method. Simultaneously the target’s magnetic field serves as an effective shield from Møller electrons by focusing them towards the beam line, while allowing detection of photons from  $4^\circ$  and maintaining the minimum permitted angle for electrons and protons at  $21^\circ$ . In addition, data were collected using a  $^{12}\text{C}$  target for the purpose of unpolarized nuclear background studies.

The large acceptance of CLAS allowed simultaneous detection of all four final-state particles of the  $ep \rightarrow ep\pi^0$  and  $\pi^0 \rightarrow \gamma\gamma$  reactions. The scattered electron was identified by a reconstructed track in the drift chambers and matching it in time with signals in the same CLAS sector of the electromagnetic calorimeter (EC) and the Čerenkov counter. The cuts on EC energy deposition effectively suppressed the background from negative pions. The proton was identified as a positively charged particle track in the magnetic field of the superconducting toroidal magnet, passing through the drift chambers

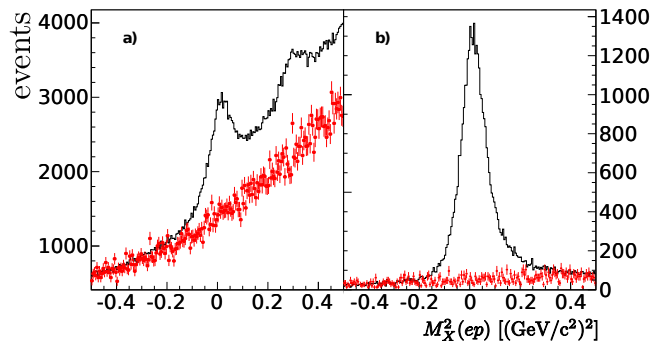


FIG. 1. (Color online) Distributions of missing mass squared of the  $(ep)$  system for the reaction  $ep \rightarrow ep\pi^0$  before (a) and after (b) the exclusivity cuts are applied. The  $^{12}\text{C}$  data (points) are normalized to the  $^{14}\text{NH}_3$  data (line).

with the correct time-of-flight information from the scintillation counters. The neutral pion decay photons were detected in the EC and the inner calorimeter (IC), which was installed downstream of the target and dedicated to the detection of the photons emitted in the forward direction. The photons were detected in the angular range between  $4^\circ$  to  $17^\circ$  in the IC and for angles greater than  $21^\circ$  in the EC.

After the identification of the four particles, the exclusive events from the  $ep \rightarrow ep\pi^0$  reaction were selected. With the 4-momenta reconstructed for all final-state particles, the event kinematics is fully known, and energy and momentum conservation can be used to develop the *exclusivity cuts*. These constraints allow for the rejection of events from unpolarized nuclear background, different channels (e.g.  $\eta$ ,  $\rho$  or  $\omega$  meson production) and reactions with an additional particle present but undetected.

Three photon-detection topologies exist: (i) both photons detected in the IC, (ii) both photons in the EC and (iii) one photon in the IC and another in the EC. The experimental resolutions of the kinematic quantities for these topologies were different due to the superior IC resolution, and thus the *exclusivity cuts* were determined independently for each case. The four cuts used for the selection of the events from exclusive  $\pi^0$  meson production were:

- (i)  $|M_X^2(ep) - M_{\pi^0}^2| < 3\sigma$ , where  $M_X^2(ep)$  is the missing mass squared of the  $ep$  system in  $ep \rightarrow epX$ ;
- (ii)  $|M_{\gamma\gamma} - M_{\pi^0}| < 3\sigma$ , where  $M_{\gamma\gamma}$  is the invariant mass of the two photons;
- (iii)  $|E_{ep\gamma\gamma}| < 3\sigma$ , where  $E_{ep\gamma\gamma}$  is the missing energy;
- (iv)  $\theta_{\pi^0 X} < 1.8^\circ, 1.2^\circ, 1.6^\circ$  for the EC-EC, IC-IC, and EC-IC topologies, respectively, where  $\theta_{\pi^0 X}$  is the angle between the measured and the kinematically reconstructed  $\pi^0$  meson in the  $ep \rightarrow epX$  system.

Figure 1 illustrates the effect of the exclusivity cuts on the missing mass of the  $ep$  system in  $ep \rightarrow epX$ . The

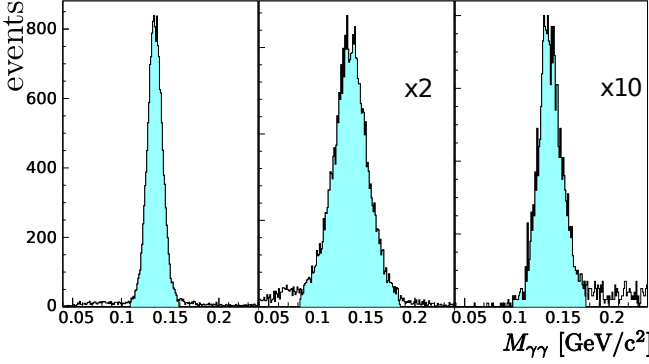


FIG. 2. Distributions of invariant mass of the two-photon system for the three different detector configurations: IC-IC, EC-EC and EC-IC from left to right. The cyan areas represent the cuts used for event selection. The last two subfigures show the factors used to scale the number of events in the histograms to the first subfigure.

contaminations from different meson production and nuclear background are greatly reduced, however even after the application of all exclusivity cuts, the events from nuclear background are still present. This remaining contamination from  $^{14}\text{N}$  was estimated using the data from carbon runs. The data from  $^{12}\text{C}$  target were normalized to  $^{14}\text{NH}_3$  by the total charge and corrected for the different areal densities of the target materials. The variations of the dilution factor with kinematics were too small to parameterize accurately, so constant dilution factors (0.9, 0.94, 0.91) were applied for three topologies (EC-EC, IC-IC and EC-IC). The contribution from unpolarized nuclear protons was less than 10% for all topologies. The small amount of background from accidental photons is visible in Fig. 2 under the invariant mass spectrum of the two photons  $M_{\gamma\gamma}$  for the three detection topologies. It was subtracted using the data in the sidebands  $(-4.5\sigma, -3\sigma) \cup (3\sigma, 4.5\sigma)$  of the  $M_{\gamma\gamma}$  distributions independently for each kinematic bin and helicity configuration. The latter is particularly important because it takes into account any polarization dependent background.

To ensure that the selected events were from the deep-inelastic regime, the kinematic cuts  $Q^2 > 1 \text{ (GeV/c)}^2$  and  $W > 2 \text{ GeV/c}^2$  were applied.  $W = \sqrt{(p+q)^2}$  is the  $\gamma^*p$  invariant mass, where  $q$  and  $p$  are the four-momenta of the virtual photon and nucleon, and  $Q^2 = -q^2$ . Then the data were divided into 110 four-dimensional kinematical bins for each of the 4 possible beam/target helicity configurations. The target and double spin asymmetries were calculated for each kinematic bin as follows:

$$A_{UL} = \frac{\sum_i (n_i^{++} + n_i^{-+}) - \sum_i (n_i^{+-} + n_i^{--})}{P_t^- \sum_i f_i (n_i^{++} + n_i^{-+}) + P_t^+ \sum_i f_i (n_i^{+-} + n_i^{--})}, \quad (4)$$

$$A_{LL} = \frac{1}{P_b} \frac{\sum_i (n_i^{++} + n_i^{--}) - \sum_i (n_i^{+-} + n_i^{-+})}{P_t^- \sum_i f_i (n_i^{++} + n_i^{--}) + P_t^+ \sum_i f_i (n_i^{+-} + n_i^{--})}, \quad (5)$$

where  $n_i^{\pm\pm}$  are the numbers of counts for each beam/target helicity configuration, normalized by the corresponding beam charge. The  $i$  index refers to the photon detection topology,  $f_i$  is the corresponding dilution factor, and  $P_t^\pm$  are the average values for the positive/negative target polarizations.

The average target polarizations  $P_t^\pm$  ( $P_t^+ \simeq 80\%$ ,  $P_t^- \simeq 74\%$ ) were extracted by dividing the product of beam and target polarizations  $P_b P_t$  by the beam polarization  $P_b$ . The former was determined by measuring the well-known spin asymmetry in elastic  $ep$  scattering [16, 17]. The latter was measured a few times during the experiment using the Møller polarimeter in Hall B. The average value was determined to be  $84\% \pm 2\%$  using the beam polarization measurements weighted by all the events.

The extraction of target and double spin asymmetries for the exclusive  $ep \rightarrow ep\pi^0$  reaction includes several sources that could induce systematic uncertainties. The main source was the event selection procedure. The exclusivity cuts were modified from  $2.5\sigma$  to  $3.5\sigma$ , and the spin asymmetries were re-analyzed for every cut alteration. The corresponding variations of asymmetries were determined to be 4.4% on average. The sideband background subtraction procedure accounted for a systematic uncertainty of 1%. The systematic uncertainties of the beam and the target polarizations, and the dilution factor, lead to an overall normalization uncertainty of 3% for double spin asymmetry and 5% for target spin asymmetry. The acceptance and binning effects were studied through careful Monte-Carlo simulation, and both effects were found to be negligible. The individual uncertainties for each kinematic bin were added in quadrature, and their values, with an average of 4.5%, were found to be smaller than statistical uncertainties for the most of bins.

The target and double spin asymmetries for exclusive  $\pi^0$  production were measured over a wide kinematic range with  $1 < Q^2 < 5 \text{ (GeV/c)}^2$ ,  $0.1 < x_B < 0.6$ , and  $0 < -t < 2 \text{ (GeV/c)}^2$ , where  $x_B = \frac{Q^2}{2pq}$  is the Bjorken variable,  $t = (p-p')^2$  is the momentum transfer to the nucleon, and  $p$  and  $p'$  are the initial and final four-momenta of the nucleon. The data were divided into two bins in the  $(Q^2, x_B)$  space, five bins in  $-t$  and eleven  $\phi$  bins with the measured asymmetries shown as a function of  $\phi$  in Fig. 3. The measurements exhibit strong azimuthal dependence for the target spin asymmetries with significant amplitudes of the  $\sin\phi$  moments and a large constant term for the double spin asymmetries.

The measured beam, target and double spin asymmetries were fitted simultaneously using six free parameters:

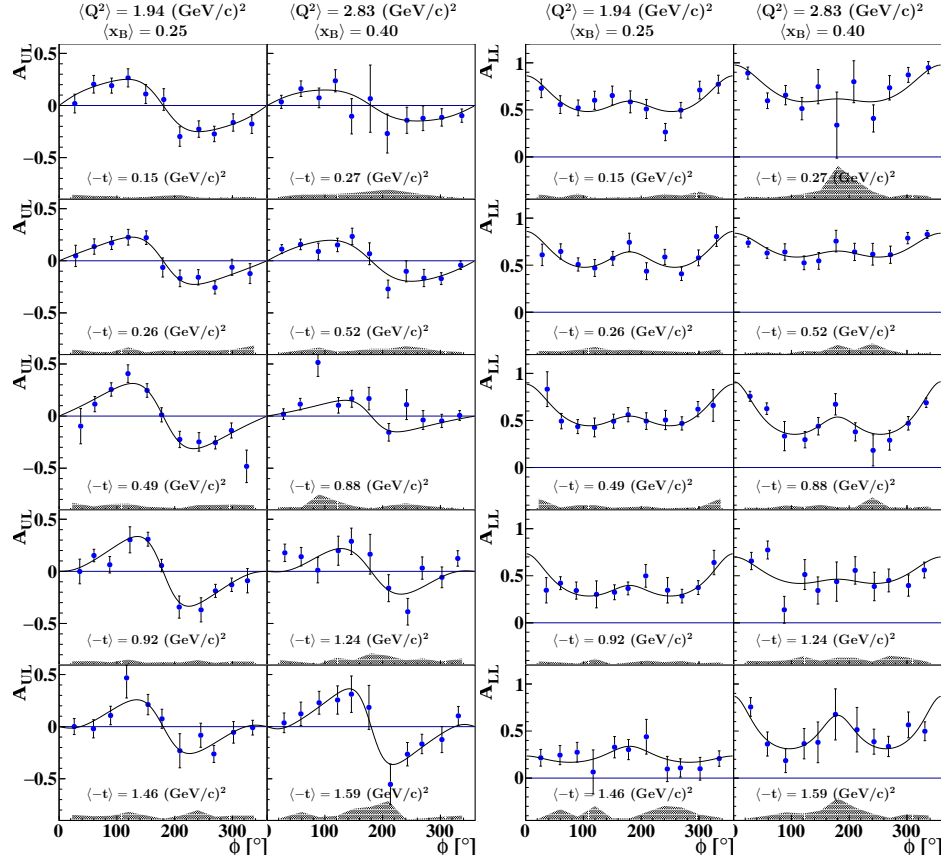


FIG. 3. Target (left panel) and double (right panel) spin asymmetries for deep exclusive  $\pi^0$  production plotted as a function of  $\phi$  for each kinematic bin in  $(Q^2, x_B)$  space (columns) and  $-t$  range (rows). The curves are simultaneous fit results described in the text. The shaded bands represent the overall systematic uncertainties.

$A_{LU}^{\sin \phi}$ ,  $A_{UL}^{\sin \phi}$ ,  $A_{UL}^{\sin 2\phi}$ ,  $A_{LL}^{const}$ ,  $A_{LL}^{\cos \phi}$  and  $A_{UU}^{\cos 2\phi}$  according to the Eqs. 1 and 2 to describe their azimuthal dependence. Due to the low statistics, the term  $A_{UU}^{\cos \phi}$  was fixed as zero to make the fit stable, because  $A_{UU}^{\cos \phi}$  is proportional to the  $\sigma_{LT}$  structure function measured in [9] and known to be small. The beam spin asymmetry was extracted in addition to the target and double spin asymmetries. This observable is important in the simultaneous fit to better constrain the unpolarized term  $A_{UU}^{\cos 2\phi}$  in the denominator common for the different polarized observables. Both  $A_{LU}^{\sin \phi}$  and  $A_{UU}^{\cos 2\phi}$  are by-products of the measurement and much better constrained from previous experiments with an unpolarized hydrogen target.

In Fig. 4 the measured asymmetry moments for  $\pi^0$  electroproduction are plotted as a function of  $-t$  in each  $(Q^2, x_B)$  bin. The theoretical predictions from two GPD-based models, GK [18] and GGL [13], are also included. They both calculate the contributions from the transverse virtual photon amplitudes using chiral-odd GPDs with  $-t$  dependence, incorporated from Regge phenomenology, but differ in the GPD parametrization methods. GGL provides the chiral-odd GPD parametrization via linear relations to chiral-even GPDs

under parity and charge conjugation symmetries in a Regge-ized diquark model. This approach allows the model to overcome the issue that very few constraints on chiral-odd GPDs exist, while chiral-even GPDs can be relatively well-constrained using deep inelastic scattering, nucleon form-factor and DVCS measurements. In the GK model, chiral-odd GPDs are constructed from the double distributions and constrained using the latest results from lattice quantum chromodynamics and transversity parton distribution functions with the emphasis on  $H_T$  and  $\bar{E}_T$ , while the contribution from the other chiral-odd GPDs are considered negligible.

The data are in better agreement with the GGL model for all the moments except  $A_{LL}^{\cos \phi}$ . The  $A_{LL}^{const}$  and  $A_{UL}^{\sin 2\phi}$  components contain only chiral-odd GPDs, whereas  $A_{LL}^{\cos \phi}$  and  $A_{UL}^{\sin \phi}$  contain both chiral-even and chiral-odd terms. The latter quantities are harder to interpret theoretically because the chiral-even and chiral-odd components cannot be separated in a model independent way, and for their description one must consider the chiral-even sector as well. However, their large magnitudes suggest sizable contributions from the chiral-odd GPDs through the interference between longitudinal and

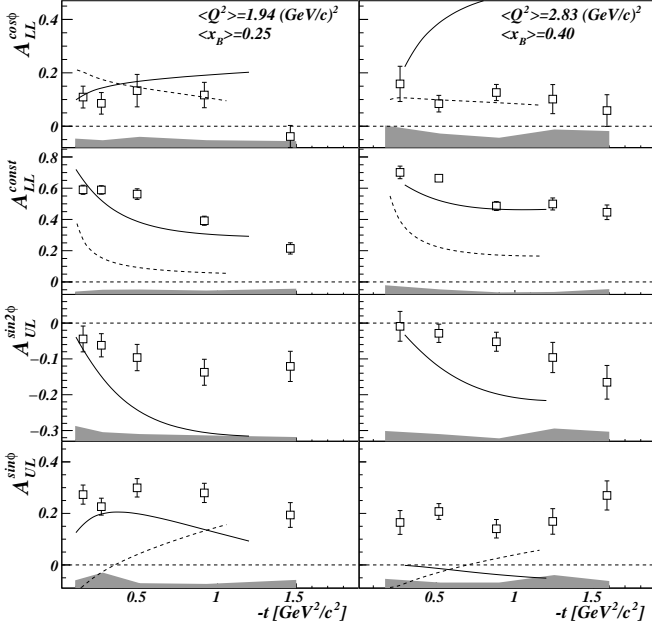


FIG. 4. The target and double spin asymmetry moments of exclusive  $\pi^0$  electroproduction as a function of  $-t$  for 2 bins in the  $(Q^2, x_B)$  plane (left and right columns). The shaded bands represent the systematic uncertainties (including fit uncertainties), and the curves show the predictions from two GPD models: GK [18] (dashed) and GGL [13] (solid). Note that the  $A_{UL}^{\sin 2\phi}$  moment is zero in the GK model, and therefore is not shown.

transverse virtual photons. The  $A_{UL}^{\sin \phi}$  term exhibits a relatively flat  $-t$  dependence similar to the observed dependence of the beam-spin asymmetry [8], but with a factor of three larger magnitude. Note that both terms are dominated by  $\langle \tilde{H} \rangle^* \langle E_T \rangle$ , but the target spin asymmetry is also enhanced by  $\langle \tilde{H} \rangle^* \langle \tilde{H}_T \rangle$  and the beam spin asymmetry is reduced by a kinematic factor. A more straightforward interpretation can be obtained for  $A_{LL}^{\text{const}}$ , which contains contributions only from chiral-odd GPDs. Its  $-t$  behavior is dominated by  $\langle H_T \rangle$  at low  $-t$  and by  $\langle E_T \rangle$  and  $\langle \tilde{H}_T \rangle$  at large  $-t$ . The data do not decrease as  $-t$  becomes small, showing the dominance of  $\langle H_T \rangle$ . Both models display a rise in  $A_{LL}^{\text{const}}$  near threshold since they rely on  $\langle H_T \rangle$  to describe it. However, the inclusion of  $\langle E_T \rangle$  and  $\langle \tilde{H}_T \rangle$  in the calculation of the double spin asymmetry in the GGL model brings their predictions in better agreement with experimental measurements. The  $A_{LL}^{\cos \phi}$  term gives access to the real part of the chiral-even and chiral-odd GPD composition  $\langle \tilde{H} \rangle^* \langle \tilde{E}_T \rangle$  and the imaginary part describes the  $A_{UL}^{\sin \phi}$  term. The overall comparison of experimental measurements with theoretical calculations demonstrates a promising new avenue to access chiral-odd GPDs and probe their kinematic dependence.

For the first time the target and double spin asymmetries for deeply virtual  $\pi^0$  meson production were

measured over a wide range of  $Q^2$ ,  $x_B$  and  $-t$ . The measurements shown in Fig. 4 are significantly different from zero in all kinematic bins. The description of the process in terms of chiral-even GPDs does not agree with experimental results. However, the interpretation of these data within recently developed GPD-based models demonstrates the significant contribution from chiral-odd GPDs, namely  $\tilde{H}_T$  and  $E_T$ . Combined with the unpolarized structure function measurements and beam spin asymmetry results for  $\pi^0$  from CLAS [8–10], these data will provide a rich set of constraints to existing chiral-odd GPD parametrizations.

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